Galactic cosmic rays (III)

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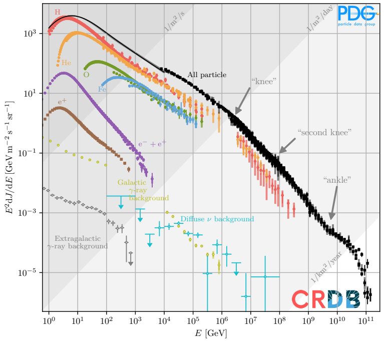
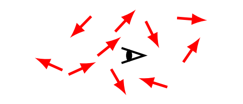
Recap (I): Fundamental observations

Spectrum



- Power law → stochastic acceleration
- Features → origin

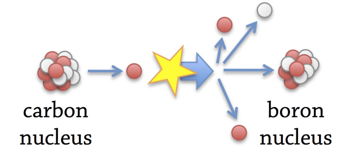
Anisotropies



- Dipole $a = \mathcal{O}(10^{-3\ldots-2})$

→ Requires isotropisation

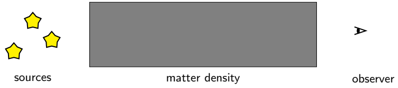
Composition



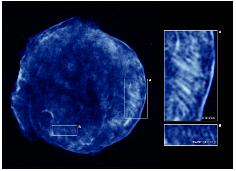
- Primaries: present in sources
- Secondaries: produced on route

→ Requires isotropisation

Recap (II): Key insights



$$\frac{dN_1}{dt} = -\frac{N_1}{t_{esc}} - N_1\Gamma_1 + Q_1$$
$$\frac{dN_2}{dt} = -\frac{N_2}{t_{esc}} - N_2\Gamma_2 + \Gamma_{1\to 2}N_1$$



The slab model

- Definition of grammage
- From B/C: average grammage of $\sim$ (a few) $\mathrm{g\,cm^{-2}}$
- Requires crossing the disk thousands of times

The leaxy-box model

- $t_{res} = \mathcal{O}(10)$ Myr
- Cosmic-ray clocks
- Grammage rigidity-dependent

Supernova remnants

1. Presence of strong shocks
2. Observation of PeV particles
3. Energetics

Recap (III): The transport equation

$$\frac{\partial \psi_j}{\partial t} = \nabla \cdot \left(\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j \right)$$ spatial diffusion and advection

$$+ \frac{\partial}{\partial p} \left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right)$$ momentum diffusion

$$+ \frac{\partial}{\partial p} \left(- \frac{\mathrm{d}p}{\mathrm{d}t} \psi_j + \frac{p}{3} \left(\nabla \cdot \mathbf{U} \right) \psi_j \right)$$ momentum change incl. adiabatic

$$- v n_{\text{gas}} \sigma_j \psi_j - \frac{\psi_j}{\tau_j}$$ spallation and decay

$$+ v n_{\text{gas}} \sum_{k>j} \sigma_{k \to j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \to j}}$$ spallation and decay

$$+ S_j$$ primary sources

Addition (I)

- Charged particles interact resonantly with wave:

$$k_{\text{res}} = r_g^{-1} \propto p^{-1}$$

- Scattering rate Γ is gyrofrequency Ω reduced by density of resonant plasma waves:

$$\Gamma(k) \simeq \Omega \frac{\delta \tilde{B}^2(k)}{B_0^2} \simeq \Omega \frac{k\, P(k)}{B_0^2}$$

- The power spectrum of resonant plasma waves is:

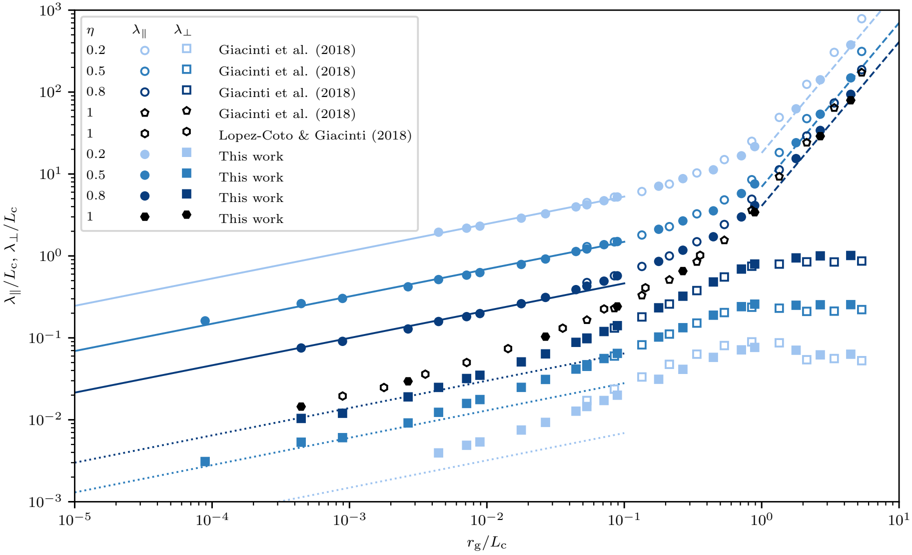
$$P(k) \sim \int \mathrm{d}^3 r\, \mathrm{e}^{i\mathbf{r}\cdot\mathbf{k}} \langle \delta\mathbf{B}(\mathbf{r}_0) \delta\mathbf{B}(\mathbf{r}_0 + \mathbf{r}) \rangle \propto k^{-5/3}$$

- Interaction with ensemble of random waves $\rightarrow$ diffusion:

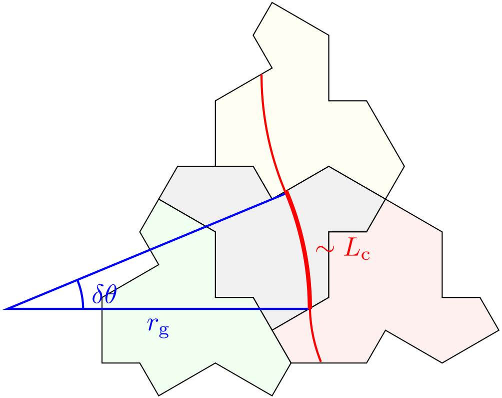
$$\kappa \simeq \frac{v^2}{3\Gamma} \propto \frac{1}{\Omega} \left(\frac{k\, P(k)}{B_0^2} \right)^{-1} \Bigg|_{k=k_{\text{res}}} \propto p^{1/3}$$

Addition (II)

Kuhlen, Mertsch, Phan (2022) [arXiv:2211.05881]



Addition (III)



- Mean-square deflection from crossing one domain:

$$\langle (\delta\theta)^2 \rangle \simeq \left(\frac{L_\mathrm{c}}{r_\mathrm{g}} \right)^2$$

- Number of domains crossed in time Δt:

$$N \simeq \frac{c \Delta t}{L_\mathrm{c}}$$

- Mean-square deflection from crossing N domains:

$$\langle (\Delta\theta)^2 \rangle = N \langle (\delta\theta)^2 \rangle \simeq \frac{c \Delta t}{L_\mathrm{c}} \left(\frac{L_\mathrm{c}}{r_\mathrm{g}} \right)^2$$

- When $\langle (\Delta\theta)^2 \rangle = 1$, $\Delta t \equiv t_\mathrm{sc}$:

$$t_\mathrm{sc} = \frac{L_\mathrm{c}}{c} \left(\frac{r_\mathrm{g}}{L_\mathrm{c}} \right)^2$$

- Spatial diffusion coefficient:

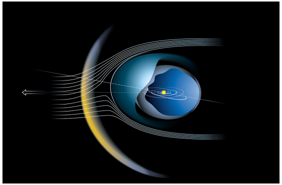
$$\kappa = \frac{c^2}{3} t_\mathrm{sc} = \frac{c L_\mathrm{c}}{3} \left(\frac{r_\mathrm{g}}{L_\mathrm{c}} \right)^2$$

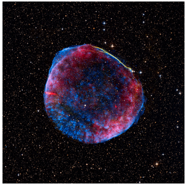
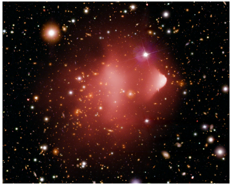
Outline

Outline

Shocks are ubiquitous

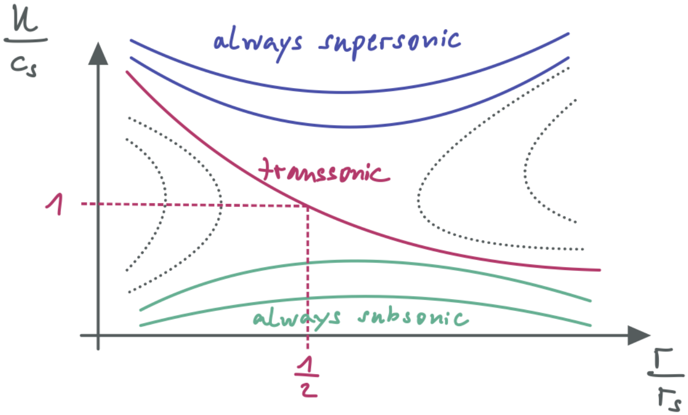
- A flow is characterised by ρ, $\mathbf{U}$, T
- In general, functions of position
- If they change abruptly, this is called a shock
- Shocks are very common in astrophysics:
  - Blast wave explosion
  - Accretion (onto star, black hole, galaxy cluster)
  - Mergers
  - Supersonic winds / outflows
  - Bow shocks (=supersonic flow around obstacle)



Shocks are inevitable

- SN is expelling material at $U_{\text{sh}} > c_s$
- Supersonic flow close to SN, subsonic flow at infinity
- Nature of supersonic and subsonic flows very different



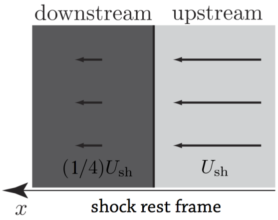
$\rightarrow$ Connection must be discontinuous: formation of shock

Parallel shock

- Consider non-relativistic shock in its rest frame
- Discontinuity in gas density and velocity:

$$\rho_2 = r\rho_1 \quad \text{and} \quad U_2 = \frac{1}{r} U_1$$

→ Gas is compressed and slowed down



Compression ratio

Depends on the ratio of specific heats γ:

$$r \simeq \frac{\gamma + 1}{\gamma - 1}$$

For ideal mono-atomic gas: $\gamma = 5/3 \Rightarrow r = 4$

The transport equation

$$\frac{\partial \psi_j}{\partial t} = \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j)$$ spatial diffusion and advection

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$$+ v n_{\text{gas}} \sum_{k>j} \sigma_{k \to j} \psi_k + \sum_{k>j} \frac{\psi_k}{\tau_{k \to j}}$$ spallation and decay

$$+ S_j$$ primary sources

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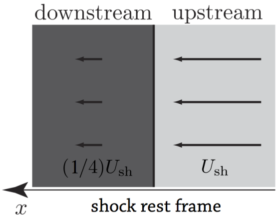
Macroscopic approach

Seminal papers in 1977/78 by Krymsky; Axford, Leer, Skaldron; Blandford, Ostriker



- Consider steady-state transport equation for phase-space density f:

$$U \frac{\partial f}{\partial x} - \frac{\partial}{\partial x} \kappa \frac{\partial f}{\partial x} - \frac{p}{3} \frac{\mathrm{d}U}{\mathrm{d}x} \frac{\partial f}{\partial p} = 0$$

- For $x \neq 0$,

$$f(x, p) = \begin{cases} g_1(p) \exp\left[\frac{x}{\kappa(p)/U} \right] + f_1(p) & \text{for } x < 0 \\ f_2(p) & \text{for } x > 0 \end{cases}$$

Macroscopic approach

Seminal papers in 1977/78 by Krymsky; Axford, Leer, Skaldron; Blandford, Ostriker

- Can derive matching conditions and find for the spectrum at shock,

$$f_2(p) = \Gamma p^{-\Gamma} \int_0^p \mathrm{d}p' \, p'^{\Gamma - 1} f_1(p') + \text{const.} \times p^{-\Gamma}$$

with spectral index $\Gamma \equiv \frac{3r}{r-1}$

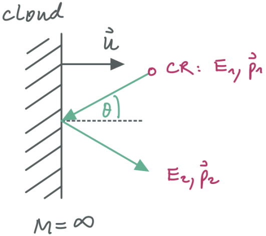
- With $r \simeq \frac{\gamma+1}{\gamma-1} = 4$, $f(0, p) \propto p^{-4} \Rightarrow \psi(0, p) = 4\pi p^2 f(0, p) \propto p^{-2}$

Strong ($r = 4$) shock accelerates CRs to p^{-2} spectrum!

Microscopic approach

Fermi (1949)

- Collision of particle with ∞ massive cloud



- Two types of collisions:
  - $\theta \in [0, \frac{\pi}{2}]$ "head-on"
  - $\theta \in [\frac{\pi}{2}, \pi]$ "trailing"

1. Transform E and p_x to cloud frame (primed):

$$E'_1 = \gamma(E_1 + U p_1 \cos\theta)$$

$$p'_{1x} = p'_1 \cos\theta' = \gamma\left(p_1 \cos\theta + \frac{U}{c^2} E_1\right)$$

Microscopic approach

1. Transform E and p_x to cloud frame (primed):

$$E_1' = \gamma(E_1 + U p_1 \cos\theta)$$

$$p_{1x}' = p_1' \cos\theta' = \gamma \left(p_1 \cos\theta + \frac{U}{c^2} E_1 \right)$$

2. Collision in cloud frame:
   - Energy conserved: $E_2' = E_1'$
   - Momentum flipped: $p_{2x}' = -p_{1x}'$
3. Transform back to observer frame:

$$\begin{aligned} E_2 &= \gamma \left(E_2' - U p_{2x}' \right) \\ &= \gamma \left(\gamma \left(E_1 + U p_1 \cos\theta \right) + U \gamma \left(p_1 \cos\theta + \frac{U}{c^2} E_1 \right) \right) \\ &= \gamma^2 \left(E_1 + 2 U p_1 \cos\theta + E_1 \left(\frac{U}{c} \right)^2 \right) \\ &= \gamma^2 E_1 \left(1 + 2 U \frac{v_1}{c^2} \cos\theta + \left(\frac{U}{c} \right)^2 \right) \end{aligned}$$

Microscopic approach

3. Transform back to observer frame:

$$E_2 = \gamma^2 E_1 \left(1 + 2U \frac{v_1}{c^2} \cos\theta + \left(\frac{U}{c} \right)^2 \right)$$

4. Expand γ^2 in U/c

$$\gamma^2 = \left(1 - (U/c)^2 \right)^{-1} \simeq 1 + (U/c)^2$$

and let $v_1 \simeq c$:

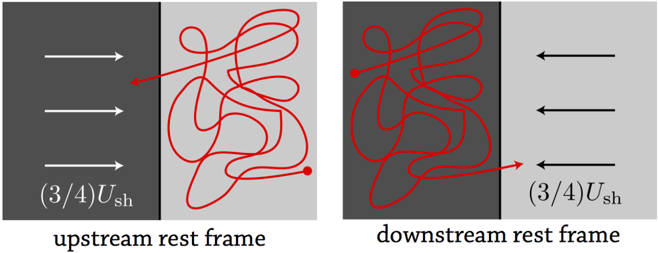
$$\Rightarrow E_2 \simeq E_1 \left(1 + 2\frac{U}{c} \cos\theta + 2 \left(\frac{U}{c} \right)^2 \right)$$

$$\Rightarrow \Delta E \equiv E_2 - E_1 = E_1 \left(2\frac{U}{c} \cos\theta + 2 \left(\frac{U}{c} \right)^2 \right)$$

$\cos\theta > 1 \quad \Rightarrow \quad$ energy gain
$\cos\theta < 1 \quad \Rightarrow \quad$ energy loss

Microscopic approach

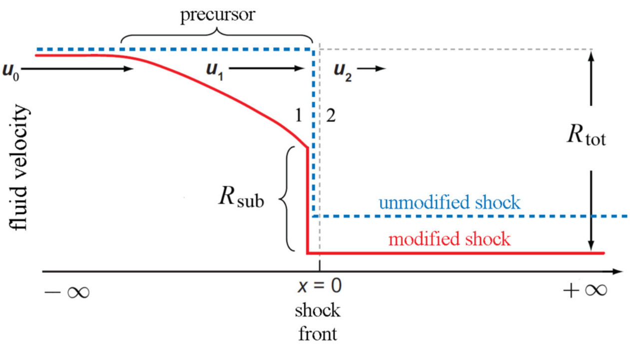
Seminal papers in 78 by Bell



- Particle crossing shock always suffers "head-on" collisions

→ Systematic energy gain, $\Delta E/E \sim (U_{sh}/c)$

Non-linear shock acceleration



Shock modification

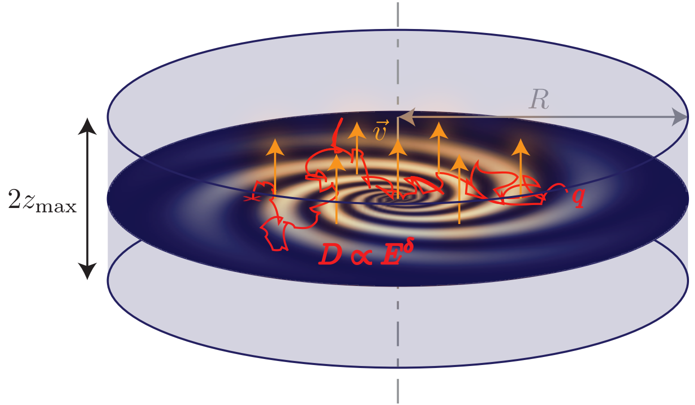
- CRs contribute to the pressure of the system
- Slow-down of flow → precursor
- Compression depends on position

→ Spectral curvature

Outline

The transport equation

$$\frac{\partial \psi_j}{\partial t} - \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j) - \frac{\partial}{\partial p}\left(p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi_j \right) + \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi_j - \frac{p}{3} (\nabla \cdot \mathbf{U}) \psi_j \right)$$
$$= S_j + \sum_{k>j} \left(v n_{\mathrm{gas}} \sigma_{k \to j} + \frac{1}{\tau_{k \to j}} \right) \psi_k - \left(v n_{\mathrm{gas}} \sigma_j + \frac{1}{\tau_j} \right) \psi_j$$



Boundary conditions: $\psi_j(r, z) = 0$ for $z = \pm z_{\mathrm{max}}$ or $r = R$

Leaky box model

- Can derive leaky box model from transport equation

$$\frac{\partial \psi_j}{\partial t} - \nabla \cdot (\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j) = q_j + \sum_{j<k} (v n_{\text{gas}} \sigma_{k \to j}) \, \psi_k - (v n_{\text{gas}} \sigma_i) \, \psi_j$$

- Integrate over CR halo, $N_j \equiv \int \mathrm{d}V \, \psi_j$:

$$\frac{\partial N_j}{\partial t} - \int \mathrm{d}V \left[\nabla \cdot \underbrace{(\kappa \cdot \nabla \psi_j - \mathbf{U} \psi_j)}_{= -\mathbf{F}_j} \right] = \frac{\partial N_j}{\partial t} + \underbrace{\int \mathrm{d}\mathbf{S} \cdot \mathbf{F}_j}_{\equiv -\frac{N_j}{\tau_{\text{esc}}}} = Q_j + \sum_{j<k} (v n_{\text{gas}} \sigma_{k \to j}) \, N_k - (v n_{\text{gas}} \sigma_i) \, N_j$$

Simplified 1D model

Simplify transport equation:

$$\frac{\partial \psi_j}{\partial t} - \kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(v n_{\text{gas}}(z) \sigma_j + \frac{1}{\tau_j} \right) \psi_j = q_j + \sum_{j<k} \left(v n_{\text{gas}}(z) \sigma_{k\to j} + \frac{1}{\tau_{k \to j}} \right) \psi_k$$

$$-\kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(2h\delta(z) v n_{\text{gas}} \sigma_j + \frac{1}{\tau_j} \right) \psi_j = 2h\delta(z) q_j + \sum_{j<k} \left(2h\delta(z) v n_{\text{gas}} \sigma_{k\to j} + \frac{1}{\tau_{k \to j}} \right) \psi_k$$

Solution

$$\psi_j(z, p) = \frac{2 z_{\text{max}} \left(q_j + \sum_{k>j} v n_{\text{gas}} \sigma_{k\to j} \psi_k \right) \mathrm{e}^{\frac{zU}{2\kappa}} \sinh \left[\frac{z_{\text{max}} - z}{z_j} \right]}{\left(2hv n_{\text{gas}} \sigma_j + U + \frac{\kappa}{z_{\text{max}}} \frac{z_{\text{max}}}{z_j} \coth \left[\frac{z_{\text{max}}}{z_j} \right] \right) \sinh \left[\frac{z_{\text{max}}}{z_j} \right]}$$

with $z_j \equiv \left(\left(\frac{U}{2\kappa} \right)^2 - \frac{1}{\tau_j \kappa^2} \right)^{-1/2}$

Simplified 1D model

Simplify transport equation:

$$\frac{\partial \psi_j}{\partial t} - \kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(v n_{\text{gas}}(z) \sigma_j + \frac{1}{\tau_j} \right) \psi_j = q_j + \sum_{j<k} \left(v n_{\text{gas}}(z) \sigma_{k \to j} + \frac{1}{\tau_{k \to j}} \right) \psi_k$$

$$-\kappa \frac{\partial^2 \psi_j}{\partial z^2} - U \frac{\partial \psi_j}{\partial z} + \left(2h\delta(z) v n_{\text{gas}} \sigma_j + \frac{1}{\tau_j} \right) \psi_j = 2h\delta(z) q_j + \sum_{j<k} \left(2h\delta(z) v n_{\text{gas}} \sigma_{k \to j} + \frac{1}{\tau_{k \to j}} \right) \psi_k$$

Solution

$$\psi_j(0, p) = \frac{2 z_{\text{max}} \left(q_j + \sum_{k>j} v n_{\text{gas}} \sigma_{k \to j} \psi_k \right) e^{\frac{zU}{2\kappa}} \sinh \left[\frac{z_{\text{max}} - z}{z_j} \right]}{\left(2 h v n_{\text{gas}} \sigma_j + U + \frac{\kappa}{z_{\text{max}}} \frac{z_{\text{max}}}{z_j} \coth \left[\frac{z_{\text{max}}}{z_j} \right] \right) \sinh \left[\frac{z_{\text{max}}}{z_j} \right]}$$

with $z_j \equiv \left(\left(\frac{U}{2\kappa} \right)^2 - \frac{1}{\tau_j \kappa^2} \right)^{-1/2} \to \infty$; evaluate at $z = 0$

$$\text{ambient CR spectrum} = \frac{\text{source spectrum}}{\text{diffusion coefficient}}$$

Green's function approach

- Solve simplified transport equation for $e^{\pm}$

$$\frac{\partial \psi_{\pm}}{\partial t} - \nabla \cdot \kappa \cdot \nabla \psi_{\pm} - \frac{\partial}{\partial E} \left(\frac{\mathrm{d}E}{\mathrm{d}t} \psi_{\pm} \right) = \delta(\mathbf{r} - \mathbf{r}_0) \delta(t) Q(E)$$

- For homogeneous energy loss rate $\mathrm{d}E/\mathrm{d}t$, energy becomes pseudo time
- Heat equation

$$\Rightarrow \psi_{\pm}(\mathbf{r}, E, t) = \left(\pi \ell^2(E, t) \right)^{-3/2} \mathrm{e}^{-|\mathbf{r}-\mathbf{r}_0|^2/\ell^2(E,t)} \frac{\frac{\mathrm{d}E}{\mathrm{d}t}(E)}{\frac{\mathrm{d}E}{\mathrm{d}t}(E_0)} Q(E_0)$$

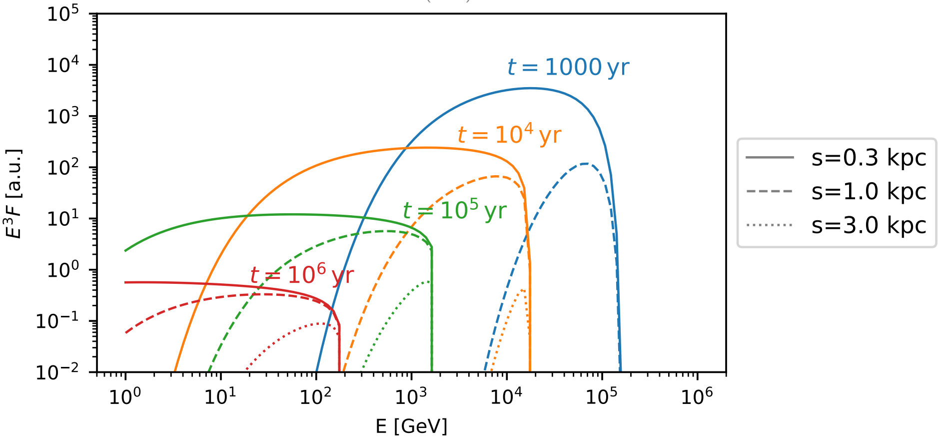
where $E_0 = E_0(E, t)$ and

$$\ell^2(E, t) = 4 \int_{E_0}^{E} \mathrm{d}E' \, \frac{\kappa(E')}{\mathrm{d}E/\mathrm{d}t}$$

Green's function

$$\psi_{\pm}(\mathbf{r}, E, t) = \left(\pi \ell^2(E, t)\right)^{-3/2} \mathrm{e}^{-|\mathbf{r}-\mathbf{r}_0|^2/\ell^2(E,t)} \frac{\frac{\mathrm{d}E}{\mathrm{d}t}(E)}{\frac{\mathrm{d}E}{\mathrm{d}t}(E_0)} Q(E_0)$$

Mertsch (2018)



with $\kappa_{xx} = \kappa_0 E^{\delta}$, $\frac{\mathrm{d}E}{\mathrm{d}t} - b_0 E^2$, $Q(E_0) \propto E_0^{-\Gamma} \exp[-E_0/E_c]$

Numerical codes

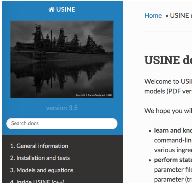
- In less restricted setups, e.g.
  - 3D
  - Inhomogeneous inputs, e.g. gas densities
  - Anisotropic diffusion
  - Self-generated turbulence

  transport equation cannot be solved analytically

→ Solve numerically

- Many codes available:

GALPROP

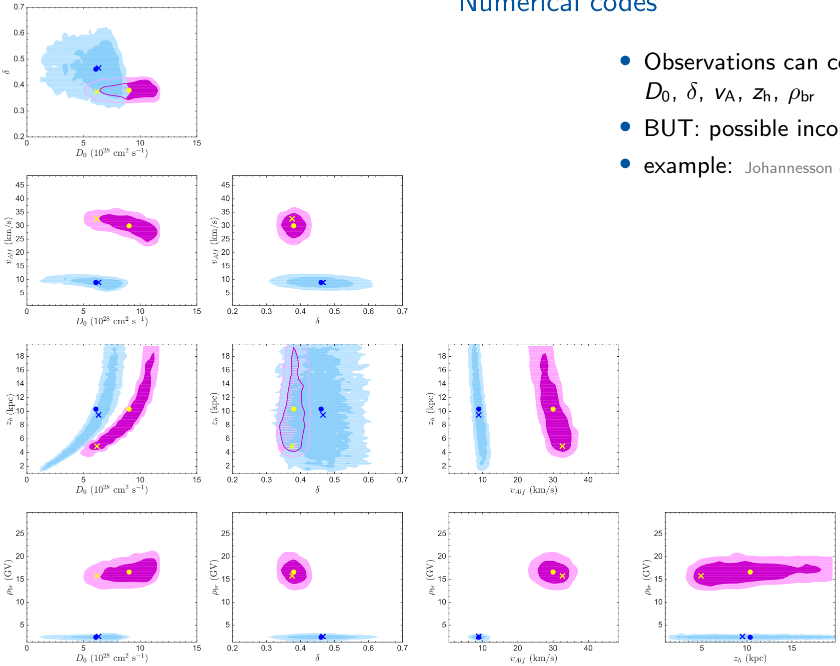


USINE

DRAGON

PICARD

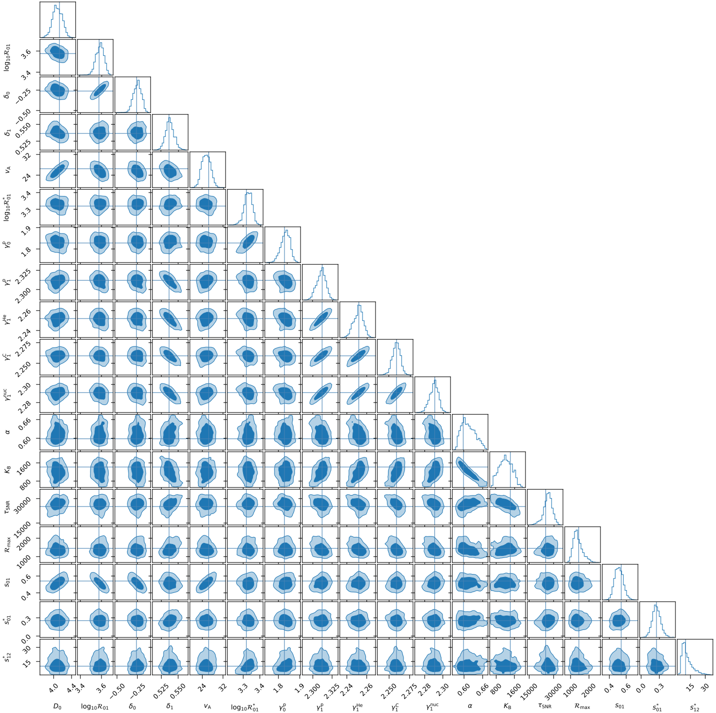
Numerical codes



- Observations can constrain free parameters, e.g.: D_0, δ, v_A, z_h, ρ_{br}
- BUT: possible inconsistencies
- example: Johannesson *et al.* (2017)

MCMC analysis

Mertsch, Vittino, Sarkar (2021)



Outline

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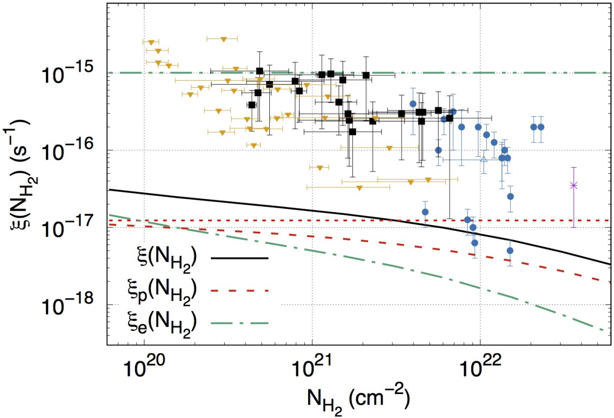
The ionisation puzzle

- Cosmic rays are ionising dense molecular clouds
- But the observed ionisation is much higher than expected
- Maybe the flux of cosmic rays elsewhere is different from what it is here?!

Phan, Morlino, Gabici (2018)



Ionisation in molecular clouds

$$p_{CR} + H_2 \to p_{CR} + H_2^+ + e^-$$
$$e^-_{CR} + H_2 \to e^-_{CR} + H_2^+ + e^-$$

$$\zeta_{H_2} \equiv (\text{production rate of } H_2^+ \text{ by cosmic rays})$$

Measurements

- Absorption of light from background star
- Line ratios sensitive to production of H_2^+
  - In diffuse clouds ($N_H \lesssim 10^{22}\,\text{cm}^{-2}$): H_3^+ produced by charge exchange
  - In dense clouds ($N_H \gtrsim 10^{22}\,\text{cm}^{-2}$): H_3^+ reacts to HCO^+, DCO^+, N_2H^+

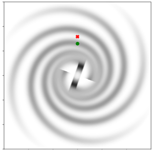
Computation

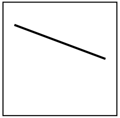
- Galactic propagation:
  - Source distribution, spectrum
  - Propagation parameters
  - → Interstellar intensity $j_{ISM} = v/(4\pi)\psi$
- Transport into cloud:
  - Energy losses
  - Ballistic or diffusive Skilling & Strong (1976); Padovani *et al.* (2009); Morlino & Gabici (2015); Phan *et al.* (2018); Ivlev *et al.* (2018)
  - → Intensity averaged over cloud $\bar{j}$
- Ionisation rate:

$$\zeta_{H_2} = 4\pi \int_{E_I}^{\infty} \mathrm{d}E\, \sigma_{ion}(E)\,(1 + \phi(E))\,\bar{j}(E)$$

Galactic propagation

- Transport equation: $$\underbrace{\frac{\partial}{\partial t}\psi - \nabla \cdot (\kappa \cdot \nabla - \mathbf{u})\psi - \frac{\partial}{\partial p}(\dot{p}\,\psi)}_{\equiv \mathcal{L}\psi} = q$$
- Green's function: $$\mathcal{L}\,\mathcal{G} = \delta^{(3)}(\mathbf{x} - \mathbf{x}')\delta(t - t')\delta(p - p')$$
- Source term: $$q = q(\mathbf{x}, t, p) = \underbrace{s(\mathbf{x}, t)}_{\text{src. density}} \cdot \underbrace{s_p(p)}_{\text{spectrum}}$$

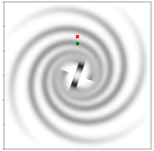


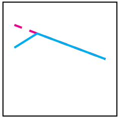


- Solution: $$\psi(\mathbf{x}, t, p) = \int \mathrm{d}\mathbf{x}'\mathrm{d}t'\mathrm{d}p'\mathcal{G}(\mathbf{x} - \mathbf{x}', t - t', p, p')\underbrace{s(\mathbf{x}', t')}_{\text{src. density}}\underbrace{s_p(p')}_{\text{spectrum}}$$

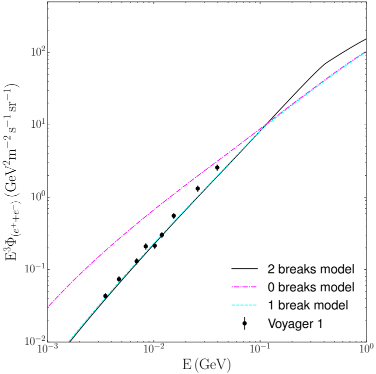
Voyager data

- Source term: $$q = q(\mathbf{x}, t, p) = \underbrace{s(\mathbf{x}, t)}_{\text{src. density}} \cdot \underbrace{s_p(p)}_{\text{spectrum}}$$





Vittino, PM, Gast, Schael, PRD **100** (2019) 043007



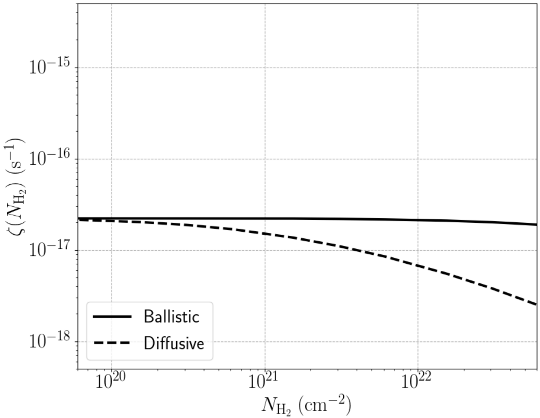
Problem # 1

Reproducing Voyager $e^+ + e^-$ requires unmotivated break in source spectrum at few hundred MeV

Cumming *et al.* (2016); Orlando (2018); Boschini *et al.* (2018); Jóhannesson *et al.* (2018); Bisschoff *et al.* (2019)

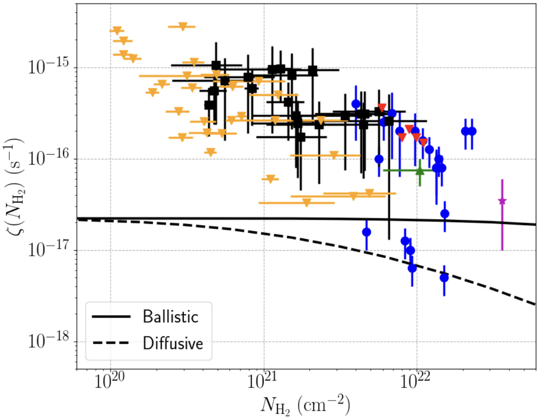
The ionisation puzzle

Padovani *et al.* (2009); Indriolo (2012); Phan, Morlino, Gabici (2018); Gabici (2021)



The ionisation puzzle

Padovani *et al.* (2009); Indriolo (2012); Phan, Morlino, Gabici (2018); Gabici (2021)



Caselli *et al.* (2018); Williams *et al.* (1998); Maret *et al.* (2007); Indriolo *et al.* (2012); Bialy *et al.* (2022)

Problem # 2

Excess and large scatter in measured ionisation rate

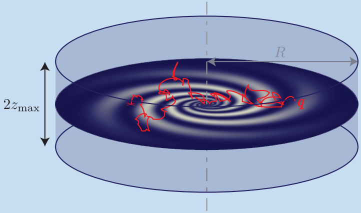
Maybe the Voyager spectrum is not representative for the spectra elsewhere?

Indriolo (2012)

Source discreteness

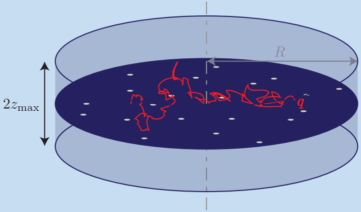
Phan, Schulze, Mertsch, Recchia, Gabici (2021)

Continuos source density



$$\psi(\mathbf{x}, t, p) = \int \mathrm{d}\mathbf{x}' \mathrm{d}t' \mathrm{d}p' \mathcal{G}(\mathbf{x} - \mathbf{x}', t - t', p, p') \underbrace{s(\mathbf{x}', t')}_{\text{src. density}} s_p(p')$$

Discrete sources



$$\psi(\mathbf{x}, t, p) = \int \mathrm{d}p' \sum_n \mathcal{G}(\mathbf{x} - \mathbf{x}_n, t - t_n, p, p') s_p(p')$$

- Assuming smooth source density is good approximation if

$$\text{(diffusion-loss length)} \gg \text{(average source separation)}$$

- However, energy losses can severely limit diffusion-loss length
- Examples:
  - High-energy $\mathrm{e}^{\pm}$ Malyshev *et al.* (2009) Blasi & Amato (2010), PM (2011, 2018), Manconi *et al.* (2017, 2019, 2020); Cholis *et al.* (2018, 2021), Evoli *et al.* (2020), Orusa *et al.* (2021)
  - Low-energy CRs

Monte Carlo simulation

Phan, Schulze, Mertsch, Recchia, Gabici (2023)

- Numerically solve transport equation for point-like sources
- Solutions on a grid in distance, age and momentum
- Interpolation allows approximating $\mathcal{G}(\mathbf{x} - \mathbf{x}', t - t', p, p')$

- Draw random distances and ages from $\underbrace{s(\mathbf{x}, t)}_{\text{src. density}}$
- Compute

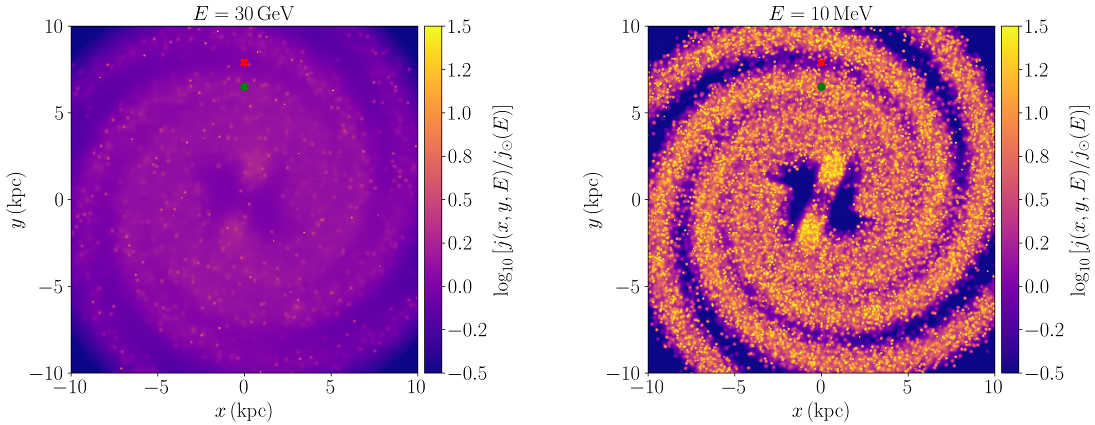
$$\psi(\mathbf{x}, t, p) = \int \mathrm{d}p' \sum_n \mathcal{G}(\mathbf{x} - \mathbf{x}_n, t - t_n, p, p') s_p(p')$$

for each member of ensemble of realisations

$\rightarrow$ Ensemble of intensities ψ

GeV vs MeV

Phan, Schulze, Mertsch, Recchia, Gabici (2023)



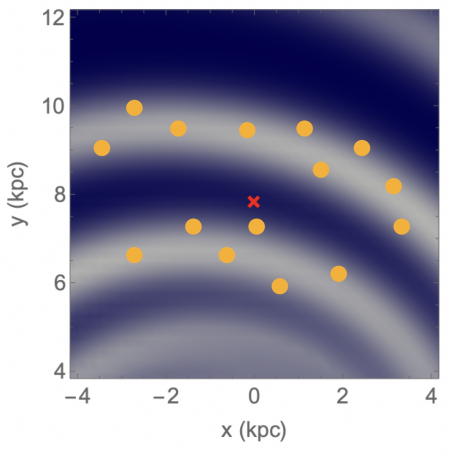
(diffusion-loss length) $\gg$ (average source separation)

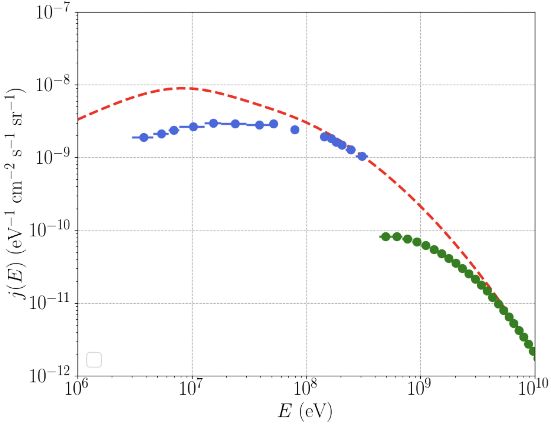
$\Rightarrow$ little fluctuation
$\Rightarrow$ smooth approximation is good

(diffusion-loss length) $\ll$ (average source separation)

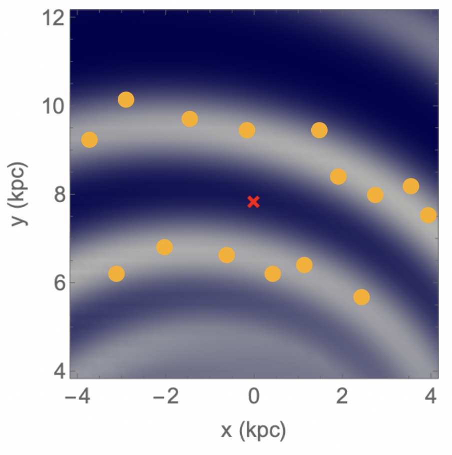
$\Rightarrow$ sizeable fluctuations
$\Rightarrow$ smooth approximation is bad

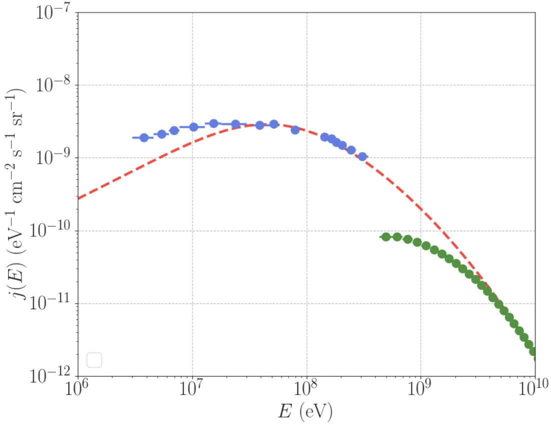
Importance of nearby sources



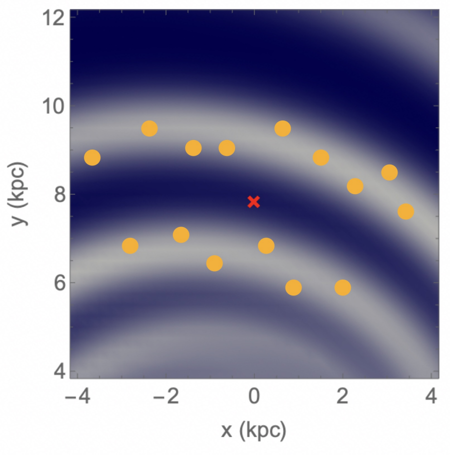


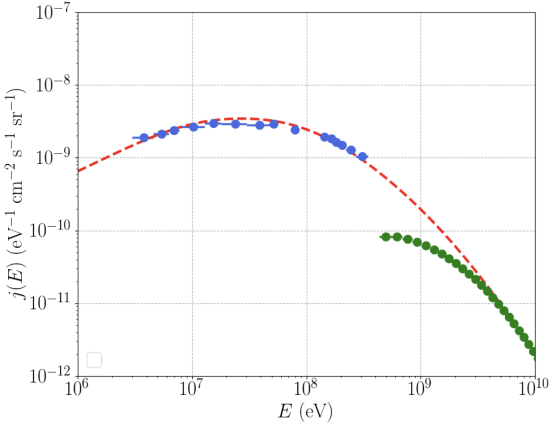
Importance of nearby sources



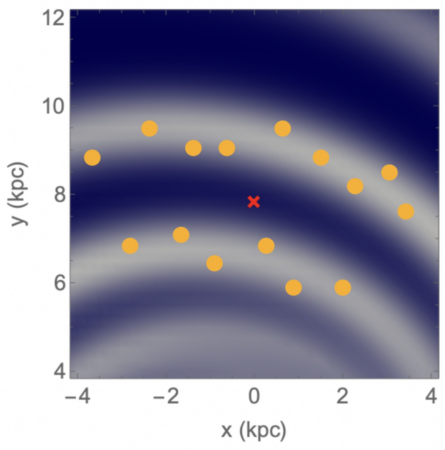


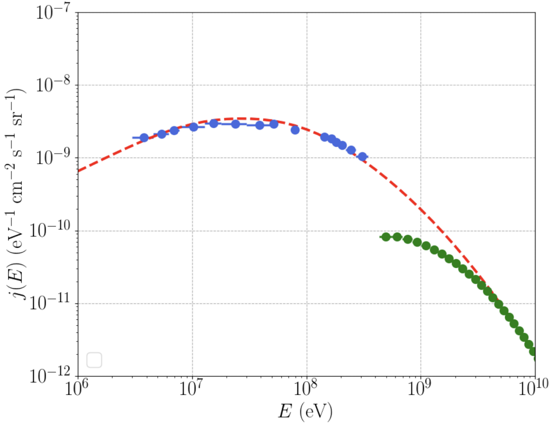
Importance of nearby sources





Importance of nearby sources

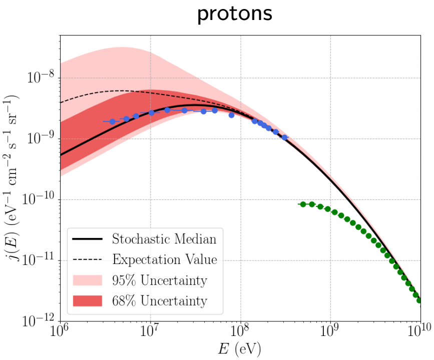


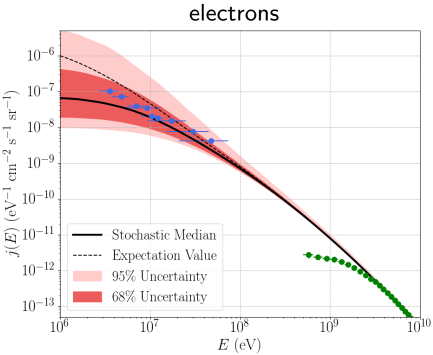


Cosmic ray flux is a stochastic quantity

Results: protons & electrons

Phan, Schulze, Mertsch, Recchia, Gabici (2021)





- Voyager 1 data inside uncertainty band

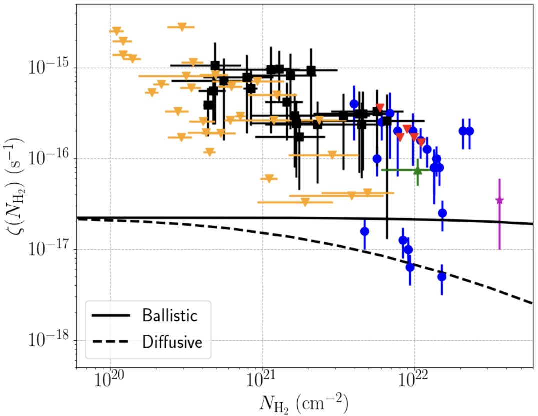
$\rightarrow$ Source discreteness effects important

Result # 1

$\rightarrow$ No need for unmotivated break in source spectrum!

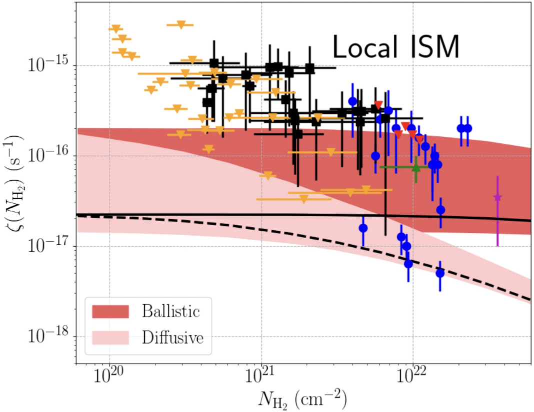
The ionisation puzzle

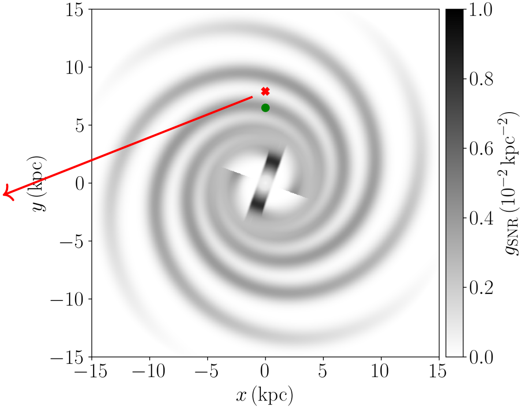
Phan, Schulze, Mertsch, Recchia, Gabici (2023)



The ionisation puzzle

Phan, Schulze, Mertsch, Recchia, Gabici (2023)



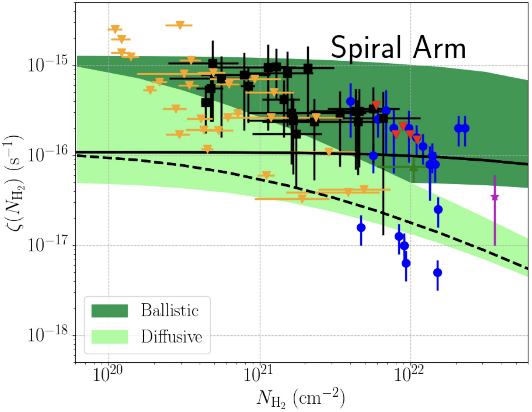


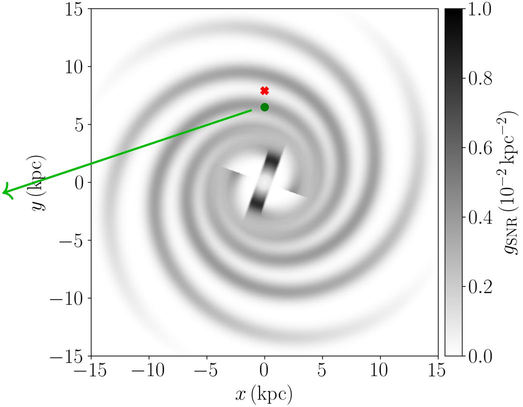
Result # 2

- Local ISM: improvement, but still too low

The ionisation puzzle

Phan, Schulze, Mertsch, Recchia, Gabici (2023)





Result # 2

- Local ISM: improvement, but still too low
- Spiral Arm: systematic shift up

Outline

Summary & Conclusions

Acceleration

Particles gain energy while scattering in converging flow

Galactic propagation

High precision experiments $\rightarrow$ significantly increased parameter space

Open questions

- e^+ excess
- Self-confinement
- A swiss-cheese galaxy
- Ionisation puzzle
- Small-scale anisotropies
- Diffuse emission

Any questions?